The Metro Line 1 in Naples: the Toledo Station construction. 
Comparison between measures and numerical analyses. 

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Abstract. Nell’ambito dell’esecuzione di scavi profondi in ambiente urbano, la questione degli spostamenti indotti dalla realizzazione d’infrastrutture nel sottosuolo, rappresenta un tema d’intensa ricerca negli ultimi anni. L’esecuzione della Stazione Toledo, lungo la nuova tratta Dante - Garibaldi della Linea 1 della Metropolitana di Napoli, dal punto di vista tecnico costituisce un’interessante raccolta delle principali problematiche affrontate durante i lavori per il compimento dell’intera opera. In questo studio si riporta una descrizione delle linee guida che hanno ispirato il progetto, le scelte executive adottate ed alcune considerazioni sugli effetti dell’adozione della tecnica del congelamento. Infine, tramite codice di calcolo alle Differenze Finite è stata compiuta una complessa analisi a ritroso del processo costruttivo di un’imponente galleria di collegamento presso la Stazione Toledo, calibrata sulle misure del programma di monitoraggio condotto dal 2005 ad oggi.

1. Introduction
This work is concerned with the analysis of a 13 m wide, 17 m high and 40 m long service tunnel execution at Toledo Station within the Metro Line 1 extension project in Naples (Italy) from the present terminal of Dante Station. The new stretch of the underground is composed of five new stations and two twin rail tunnels with a length of 5 km. Four stations out of five have the access shaft centred with the twin rail tunnels. On the contrary, Toledo Station has the shaft located laterally and a large size service tunnel connects it to the rail and pedestrian access tunnels, starting from the access shaft. The tunnel is located in the historical centre, under a deeply urbanized area in volcanic soil (loose pozzolana silty sand and tuff) with a hydrostatic head of 27 m.
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For stabilizing the tunnel crown in loose volcanic soil during the excavation, it was decided to adopt the Artificial Ground Freezing method among the various options of ground improvement techniques. AGF is based on withdrawing heat from the soil and the process converts in-situ pore water into ice, so that, the ice binds the soil particles imparting strength and impermeability to the frozen soil mass. In this work, attention is especially focused on the freezing-thawing process and deformations due to the AGF technique application are examined. Along the entire surface around the station, an extensive monitoring program was performed during the entire construction progress to check the development of vertical displacements and changing in groundwater level. Here, the service tunnel construction effects are analysed and results of Finite Difference analyses are discussed and compared with recorded data. Through a complex back-analysis, a parametric study was carried out to properly simulate the connection between groundwater withdrawal and land subsidence resulting from the excavation and to individuate appropriate soil parameters for frozen and thawed conditions, on developing a three-dimensional model with Flac3D.

2. The project

In Naples, a Metro Line 1 extension is being constructed from the present terminal of Dante Station. The metro design develops in a site geologically composed by two different volcanic soils: a cohesionless loose silty sand (pozzolana) on the top and a soft fractured rock on the bottom (tuff). In order to reduce the displacements induced by the excavation, minimizing possible negative effects on the existing buildings, the project line, with a hydrostatic head up to 40m, was completely under the tuff avoiding works in the loose soil.

The Toledo Station peculiarity is that the shaft is not centred with the twin rail tunnels and a large size service tunnel connects it to the rail and pedestrian access tunnels (Fig. 1). The service tunnel was one of the most critical works, because of its dimensions (over 8000, 13 m wide, 17 m high and 40 m long), located downtown under a urbanized area with a hydrostatic head of about 27 m. This tunnel has both temporary and permanent function. The temporary function was to give a suitable room to build four platform and two pedestrian tunnels. Once the station will be finished, the permanent function will be to allow the transit of people from one track to the other, and to connect the platforms with the Quartieri Spagnoli secondary access by means of a pedestrian tunnel.
Because of the closeness of the tunnel crown, immersed in the loose soil, to the building foundations and various utilities, two different soil improvement methods were used: grouting with Multi Packer Sleeved Pipe (MPSP) at the sides and invert in tuff (suitable rock for conventional grouting, due to its average global hydraulic conductivity), and the Artificial Ground Freezing (AGF) at the crown in pozzolana (Fig. 2). Cement and chemical grouting was carried out through sub-vertical grouting pipes, installed from the drift located 10 m above the crown, in pozzolana sand and just above the groundwater level. The AGF was carried out through freeze-lances, providing a closed chamber consisting of pseudo-cylindrical frozen ground bulbs. Besides, an end plug was made by jet-grouting and grouting.

Fig. 2. Transversal and longitudinal tunnel section with soil improvement techniques adopted
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The service tunnel excavation was a staged construction, carried out through the following steps:

- opening of the excavation front at the crown (for a depth of 6 m from the crown centre line) with 4 m progress of the excavation and casting of 3 m long first concrete liner (0.75 m thick);
- excavation of the sidewalls (7.5 m deep) and casting of the first liner with application of 5 levels high tensile steel alloy Dywidag bar 2 m spaced;
- excavation of the sidewalls bases and invert construction;
- opening of the six connections through the service tunnel liner;
- completion of the service tunnel structure by placement of a second concrete liner (0.80 m thick) separated from the first by a waterproofing layer.

Artificial freezing method is widely used in the civil underground excavation and supporting projects these years. It is perhaps the only technology that can create both a water tight seal and provide a temporary load carrying capability. It is superior to other ground treatment methods because it is well suitable for almost all kind of layers and has usually less environmental impact. At the Toledo Station service tunnel, a combination of two procedures, the liquid nitrogen method (for the freezing phase) and brine method (for the maintenance phase), was used. The aim of AGF was to protect the first phase excavation interesting the tunnel crown. For this reason a system of freezing-lances was installed:

- n. 16 + 15 horizontal lances 40 m long, located around the crown and drilled by Horizontal Directional Drilling (HDD) from the access shaft;
- n. 73 + 73 sub-vertical lances 18 m long, drilled from the drift and located along four lines parallel to the tunnel, with the toe embedded into the treated tuff.

Whereas grouting technologies can typically use the geotechnical parameters developed from a usual geotechnical study, ground freezing must consider specific data collection and additional investigation that are typically beyond most geotechnical studies. Therefore, a test programme was conducted to verify the estimated soil parameters for frozen and thawed conditions.

On purpose, an appropriate device was built for performing triaxial compression tests in cryogenic conditions with different values of
temperature and confining pressure. It was also expected to carry out simple compression tests and indirect tensile strength tests on frozen specimens at different temperatures. In the complex, the following tests were performed on frozen samples at temperatures of -5, -10 and -20 °C:

- triaxial compression tests on frozen and thawed specimens;
- uniaxial compression tests on frozen specimens;
- tensile strength tests on frozen specimens.

These tests (an example of the results in Fig. 3) provided reliable information about the values of cohesion and tensile strength of frozen pozzolana.

Fig. 3. Volume, temperature and stress-time history during a freezing - thawing cycle

\[ T = -10°C, \sigma = 200kPa, \nu = 0.06mm/min \]

Comparing the stress-strain curves of frozen sandy soil under different temperatures, revealed that temperature is an important factor in the deformation of frozen soil. With a decrease in temperature, unfrozen water content in the frozen soil decreased while ice content increased, determining the growth of both the cementing bond and the volume of the frozen soil at the same time during freezing. In addition, with a reduction of the frozen soil temperature from -5°C to -10°C, the compressive strength almost doubled and also the failure form of frozen soil tended to change.

3. The monitoring
An intense monitoring program was carried out to control the impact of the Toledo Station execution in such a dense urban area, particularly to check the development of vertical displacements and changing in groundwater level. Since 2005, measurements were performed on surface benchmarks and such measures were constantly related to the different construction phases of the station, including therefore, also the operations for the execution of the service tunnel (July 2006 - March 2007). Besides, to
analyse the ground surface subsidence evolution, a Minimum Curvature statistical interpolation technique was applied to the monitored output data, in order to produce contour lines of the subsidence displacements (Fig. 4).

In order to verify possible correlations between piezometric heads reductions due to water seepage and ground surface settlements, these two measures have been compared all over the study area from 2006 to 2011. In particular, looking at Fig. 5 with the plot of the measured settlements of the benchmark 146 and the piezometric levels of the near piezometers S6, S7, S8 and PZ3, although the measures of individual piezometers do not offer continuous monitoring of groundwater head, observing the readings on the whole, however they offer an indication of the clear correlation between changing in groundwater level and ground subsidence observed.
4. Numerical analyses

Though most ground movement occurrences are apparently predictable in light of present knowledge, it is evident that we do no yet posses adequate analytic techniques to accurately model all of the complex multidimensional transient conditions, which exist for most AGF projects. However, up to now relatively only little information exists on the effects of simulation of frozen-thawed soil in numerical analyses. For that reason, a case study is presented.

Flac3D was employed in this work to build a numerical model and reproduce the service tunnel realization at Toledo Station and to analyse the impact of the tunnel on existing structures and services. Surface settlements depending on both the excavation method and the type of tunnel reinforcement, are definitely a three-dimensional problem.

In a 3D FD-simulation the service tunnel excavation was modelled: taking the symmetry into account, the domain was 50 m wide, 56 m deep and 80 m long and the mesh consisted of about 127000 hexahedral elements to preserve the accuracy of the plasticity computation. The groundwater level was assumed to be 21 m below the ground surface and the pozzolana and tuff layers were modelled using the Mohr-Coulomb failure criterion with drained behaviour.
As a result of in situ tests and laboratory tests, the soil parameters in Tab. 1 were adopted in the model:

<table>
<thead>
<tr>
<th>Pozzolana</th>
<th>Tuff</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ [kN/m$^3$]</td>
<td>14</td>
</tr>
<tr>
<td>$\gamma'$ [kN/m$^3$]</td>
<td>16</td>
</tr>
<tr>
<td>E [kN/m$^2$]</td>
<td>40000</td>
</tr>
<tr>
<td>c [kN/m$^3$]</td>
<td>0.1</td>
</tr>
<tr>
<td>$\varphi$ [$^\circ$]</td>
<td>36</td>
</tr>
<tr>
<td>T. strength [kN/m$^3$]</td>
<td>0</td>
</tr>
<tr>
<td>$\beta$ [°]</td>
<td>0.3</td>
</tr>
<tr>
<td>Perm. [m/s]</td>
<td>3E-04</td>
</tr>
</tbody>
</table>

In particular, through a complex back-analysis, a parametric study was carried out to individuate appropriate values of Young’s Modulus and friction angle of frozen and thawed pozzolana and to properly simulate the connection between groundwater withdrawal and land subsidence resulting from the excavation, performing a groundwater flow calculation. Results of several analyses carried out have allowed the identification of the mechanical properties of frozen and thawed pozzolana reported in Tab. 2:

<table>
<thead>
<tr>
<th>Pozzolana</th>
<th>Frozen pozzolana</th>
<th>Thawed pozzolana</th>
<th>several</th>
</tr>
</thead>
<tbody>
<tr>
<td>E [kN/m$^2$]</td>
<td>40000</td>
<td>100000</td>
<td>25000</td>
</tr>
<tr>
<td>c [kN/m$^3$]</td>
<td>0.1</td>
<td>160</td>
<td>0.1</td>
</tr>
<tr>
<td>$\varphi$ [°]</td>
<td>36</td>
<td>36</td>
<td>23.2</td>
</tr>
<tr>
<td>T. strength [kN/m$^3$]</td>
<td>0</td>
<td>650</td>
<td>0</td>
</tr>
</tbody>
</table>

Comparing the calculated and measured displacements orthogonally to the tunnel centre line at a distance form the access shaft of 21 meters, quantitative results determined by this analysis sufficiently agreed with practically measured settlement curves regarding to the maximum
displacement values in each construction phase, but the calculated subsidence depression involved a larger zone compared to the effective measured depression (Fig. 6) and this difference could suggest a higher initial stiffness than assumed in the upper layers.

The three-dimensional analysis confirmed the influence of the shape effect on the displacements spatial distribution, appearance not deduced from the two-dimensional simulation of the tunnel excavation indefinitely extended in a plane (Fig. 7).

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**Fig. 6. Comparison between measured settlements and calculation data**

The three-dimensional analysis confirmed the influence of the shape effect on the displacements spatial distribution, appearance not deduced from the two-dimensional simulation of the tunnel excavation indefinitely extended in a plane (Fig. 7).

**Fig. 7. Calculated settlements in the 3D domain**
Comparing the vertical displacements calculated during each modelled phase with those measured on site during the execution of the works for the construction of the service tunnel (benchmark 146), looking at the Fig. 8, we can say that the general settlements trend in the numerical simulation reproduced satisfactorily the site measures.

Fig. 8. Comparison between measures and calculation data during each construction phase

REFERENCES


CAVUOTO F., COLOMBO G. & GIANNELLI F., An alternative tunnelling approach to accelerate urban underground excavation under water, in International fib Symposium, Tailor made concrete structures, Amsterdam, 2008, pp. 993-999.

